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Effects of R-parity violation on CP asymmetries in $\Lambda_b \to p\pi$ decay

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Abstract

We have studied new CP violating effects in $\Lambda_b \to p\pi$ decay mode, that can arise in Minimal Supersymmetric Standard Model with R-parity violation. We have estimated how much R-parity violation modifies the Standard Model predictions for CP asymmetries within the present bounds. We found that in the R-parity violating model, the rate asymmetry (a_{cp}) is suppressed (about 10 times) and the asymmetry parameter $A(\alpha)$ is enhanced (approximately $\mathcal{O}(10^2)$ times) with respect to the SM predictions.

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One of the most important objects of the upcoming experiments at B factories is to search for CP violation in as many B decay modes as possible so as to establish the pattern of CP violation among various B decays [1]. This then may allow for an experimental test not only of the Standard Model (SM) Cabibbo-Kobayashi-Maskawa (CKM) paradigm of CP violation, but also many extensions of the SM that often contain new sources of CP violation. It is well known that CP violating B decays might constitute an important hunting ground for new physics. This is particularly so since many CP violating asymmetries related to B decays are predicted to be small in SM, are likely to be measured with high precision in the upcoming B factories. Measurements larger than the SM predictions would definitely signal the presence of new physics. It is also interesting to study CP violation in bottom baryon system in order to find the physical channels which may have large CP asymmetries, even though the branching ratios for such processes are usually smaller than those for the corresponding bottom mesons. Recently some data on the bottom baryon Λ_b have appeared. For instance, OPAL has measured its lifetime and the production branching ratio for the inclusivs semileptonic decay $\Lambda_b \to \Lambda l^- \bar{\nu} X$ [2]. Furthermore, mesurements of the nonleptonic decay $\Lambda_b \to \Lambda J/\psi$ has also been reported [3]. Certainly we expect more data in the future in the bottom baryon sector. In this paper we intend to study CP violation in the nonleptonic $\Lambda_b \to p\pi$ decay in the Minimal Supersymmetric Standard Model (MSSM) with R-parity violation [4]. The MSSM has been widely considered as a leading candidate for new physics beyond SM. In supersymmetric theories 'R-parity' is a discrete symmetry under which all standard model particles are even while their superpartner are odd. It is defined as $R = (-1)^{(3B+L+2S)}$, where S is the spin, B is the baryon number and L is the lepton number of the particle. An exact R-parity implies that superparticles could be produced in pairs and the lightest supersymmetric particle (LSP) is stable. However, B and L conservations are not ensured by gauge invariance and therefore it is worhwhile to investigate what happens to the CP asymmetries when R-parity is violated.

The most general Lorentz-invariant amplitude for the decay $\Lambda_b \to p\pi^-$ can be written as [5]

$$i\bar{u}_p(p_f)(a + b\gamma_5)u_{\Lambda_b}(p_i) \tag{1}$$

The corresponding matrix element for $\bar{\Lambda}_b \to \bar{p}\pi^+$ is then

$$i\bar{v}_{\bar{p}}(p_f)(-a^* + b^*\gamma_5)v_{\bar{\Lambda}_b}(p_i) \tag{2}$$

It is convenient to express the transition amplitude in terms of S-wave (parity violating) and P-wave (parity conserving) amplitudes S and P as

$$S + P\sigma \cdot \hat{\mathbf{q}} \tag{3}$$

where $\mathbf{q}$ is the proton momentum in the rest frame of Λ_b baryon and the amplitudes S and P are :

$$S = a\sqrt{\frac{\{(m_{\Lambda_b} + m_p)^2 - m_\pi^2\}}{16\pi m_{\Lambda_b}^2}} \qquad P = b\sqrt{\frac{\{(m_{\Lambda_b} - m_p)^2 - m_\pi^2\}}{16\pi m_{\Lambda_b}^2}} \tag{4}$$

The experimental observables are the total decay rate Γ and the decay parameters α, β and γ which govern the decay-angular distribution and the polarization of the final baryon. The decay rate is given as

$$\Gamma = 2|\mathbf{q}|\{|S|^2 + |P|^2\} \tag{5}$$

and the dominant asymmetry parameter (α) is given as

$$\alpha = \frac{2Re(S^* P)}{\{|S|^2 + |P|^2\}} \tag{6}$$

Similar observables for the antihyperon decays are $\bar{\Gamma}$ and $\bar{\alpha}$ are given as

$$\bar{\Gamma} = 2|\mathbf{q}|\{|\bar{S}|^2 + |\bar{P}|^2\}\ , \qquad \bar{\alpha} = \frac{2Re(\bar{S}^* \bar{P})}{\{|\bar{S}|^2 + |\bar{P}|^2\}} \tag{7}$$

For $\Lambda_b \to p\pi^-$ decay the CP violating rate asymmetry in partial decay rate (a_{cp}) and aymmetry parameter ($A(\alpha)$) are defined as follows,

$$a_{cp} = \frac{\Gamma(\Lambda_b \to p\pi^-) - \Gamma(\bar{\Lambda}_b \to \bar{p}\pi^+)}{\Gamma(\Lambda_b \to p\pi^-) + \Gamma(\bar{\Lambda}_b \to \bar{p}\pi^+)}\ , \tag{8}$$

$$A(\alpha) = \frac{\alpha + \bar{\alpha}}{\alpha - \bar{\alpha}}\ , \tag{9}$$

A nonzero value for a_{cp} and $A(\alpha)$ will signal CP violation. The existence of such CP asymmetries require the interference of two decay amplitudes with different weak and strong phase differences. The weak phase difference arises from the superposition of various penguin contributions and the usual tree diagrams while the strong phases are induced by final state interactions (FSI). At the quark level, the strong phase diffences arise through the absorptive parts of penguin diagrams (hard final state interactions) [6] and nonperturbatively (soft final state interactions) [7]. In the absence of an argument that the parton-hadron duality should hold in exclusive processes, one can not exclude that the weak transition matrix elements receive phases originating from soft FSI. However the effects of soft FSI are extremely difficult to quantify. In the absence of a reliable theoretical calculation for soft FSI, we make the usual approximation of retaining the absorptive part from quark level calculation (hard FSI) for strong phase differences in our analysis.

We shall first consider the SM contributions to the transition amplitude. The effective Hamiltonian $\mathcal{H}_{eff}$ for the decay process $\Lambda_b \to p\pi^-$ is given as

$$\mathcal{H}_{eff} = \frac{G_F}{\sqrt{2}}\Big\{V_{ub}V_{ud}^*[c_1(\mu)O_1^u(\mu) + c_2(\mu)O_2^u(\mu)] - V_{tb}V_{td}^*\sum_{i=3}^{10} c_i(\mu)O_i(\mu)\Big\} + \text{h.c.}\ , \tag{10}$$

where $O_{1,2}$ are the tree level current-current operators, O_{3-6} are the QCD and O_{7-10} are the electroweak penguin operators which are explicitly given in Ref. [8], c_i's are the Wilson coefficients, which take care of the short-distance QCD corrections, are scheme and scale dependent. These unphysical dependences are cancelled by the corresponding scheme and scale dependences of the matrix elements of the operators. However, in the factorization approximation, the hadronic matrix elements are written in terms of form factors and decay constants, which are scheme and scale independent. So to achieve the cancellation, the various one loop corrections are absorbed into the effective Wilson coefficients c_i^{eff}, which

are scheme and scale independent. The values of the effective Wilson coefficients for $b \to d$ transitions are explicitly evaluated in Ref. [8] as :

$$\begin{array}{llll} c_1^{eff} = 1.168 & c_2^{eff} = -0.365 & c_3^{eff} = 0.0224 + i0.0038 & c_4^{eff} = -(0.0454 + i0.0115) \\ c_5^{eff} = 0.0131 + i0.0038 & c_6^{eff} = -(0.0475 + i0.0115) & c_7^{eff}/\alpha = -(0.0294 + i0.0329) & \\ c_8^{eff}/\alpha = 0.055 & c_9^{eff}/\alpha = -(1.426 + i0.0329) & c_{10}^{eff}/\alpha = 0.48 & \end{array} \tag{11}$$

These one loop corrections (to get c_i^{eff}'s) result in imaginary parts for (c_i^{eff}'s) due to virtual quarks going on their mass shell.

The matrix elements of the operators can be calculated using the factorization approximation. In this approximation the hadronic matrix elements of the four quark operators $(\bar{d}b)_{V-A}(\bar{u}d)_{V-A}$ split into products of matrix elements one involving pion decay constant and the other dealt the baryonic form factors. The matrix elements of the $(V-A)(V+A)$ i.e., (O_6 and O_8) operators can be obtained by Fierz reordering and using the Dirac equation as,

$$\langle p\pi|O_6|\Lambda_b\rangle = -2\sum_q \langle \pi|\bar{d}(1+\gamma_5)q|0\rangle\langle p|\bar{q}(1-\gamma_5)b|\Lambda_b\rangle \tag{12}$$

Using the Dirac equation the matrix element can be rewritten as

$$\langle p\pi|O_6|\Lambda_b\rangle = \Big[R_1\langle p|V_\mu|\Lambda_b\rangle - R_2\langle p|A_\mu|\Lambda_b\rangle\Big]\langle \pi|A_\mu|0\rangle\ , \tag{13}$$

with

$$R_1 = \frac{2m_\pi^2}{(m_b - m_u)(m_d + m_u)}\ , \qquad R_2 = \frac{2m_\pi^2}{(m_b + m_u)(m_d + m_u)}\ , \tag{14}$$

where the quark masses are the current quark masses. The same relation works for O_8.

Thus under the factorization approximation the baryon decay amplitude is governed by a decay constant and baryonic transition form factors. The general expression for the baryon transition is given as

$$\begin{aligned} \langle p(p_f)|V_\mu - A_\mu|\Lambda_b(p_i)\rangle = \bar{u}_p(p_f)\Big\{ & f_1(q^2)\gamma_\mu + if_2(q^2)\sigma_{\mu\nu}q^\nu + f_3(q^2)q_\mu \\ & - [g_1(q^2)\gamma_\mu + ig_2(q^2)\sigma_{\mu\nu}q^\nu + g_3(q^2)q_\mu]\gamma_5\Big\}u_{\Lambda_b}(p_i)\ , \end{aligned} \tag{15}$$

where $q = p_i - p_f$. The values of the form factors at maximum momentum transfer are evaluated in nonrelativistic quark model and their q^2 dependence are determined using the pole dominance model [9] with values as,

$$f_1(m_\pi^2) = 0.043 \quad m_i f_3(m_\pi^2) = -0.009 \quad g_1(m_\pi^2) = 0.092 \quad m_i g_3(m_\pi^2) = -0.047\ , \tag{16}$$

where the particle masses are taken from [10].

Hence one obtains the amplitude for the decay mode $\Lambda_b \to p\pi^-$ as (where the factor $G_F/\sqrt{2}$ is suppressed)

$$
\begin{aligned}
A(\Lambda_b \to p\pi^-) = i f_\pi \bar{u}_p(p_f) \Big[\Big\{ & \lambda_u \left(a_1 + a_4 + a_{10} + (a_6 + a_8) R_1 \right) + \lambda_c \left(a_4 + a_{10} + (a_6 + a_8) R_1 \right) \Big\} \\
& \times \Big(f_1(m_\pi^2)(m_i - m_f) + f_3(m_\pi^2) m_\pi^2 \Big) \\
& + \Big\{ \lambda_u \left(a_1 + a_4 + a_{10} + (a_6 + a_8) R_2 \right) + \lambda_c \left(a_4 + a_{10} + (a_6 + a_8) R_2 \right) \Big\} \\
& \times \Big(g_1(m_\pi^2)(m_i + m_f) - g_3(m_\pi^2) m_\pi^2 \Big) \gamma_5 \Big] u_{\Lambda_b}(p_i) \ , \qquad (17)
\end{aligned}
$$

where m_i and m_f are the masses of the initial and final baryons respectively. The coefficients $a_1,\ a_2 \cdots\ a_{10}$ are combinations of the effective Wilson coefficients given as

$$
a_{2i-1} = c_{2i-1}^{eff} + \frac{1}{(N_c)} c_{2i}^{eff} \quad a_{2i} = c_{2i}^{eff} + \frac{1}{(N_c)} c_{2i-1}^{eff} \qquad i = 1, 2 \cdots 5 \ , \qquad (18)
$$

where N_c is the number of colors, taken to be $N_c = 3$ for naive factorization. Thus one obtains the S and P-wave amplitudes using eqns. (1), (4) and (17), in units of (10^{-9}) as

$$
\begin{aligned}
S &= \lambda_u (34.603 - 0.7115 i) - \lambda_c (2.782 + 0.7115 i) \\
P &= \lambda_u (74.056 - 1.521 i) - \lambda_c (5.95 + 1.521 i) \ , \qquad (19)
\end{aligned}
$$

with $\lambda_i = V_{ib} V_{id}$. Now we shall proceed to evaluate the R-parity violating ($\not{R}_p$) amplitude. In the MSSM the most general R-parity violating superpotential is given as

$$
W_{\not{R}_p} = \lambda_{ijk} L_i L_j E_k^c + \lambda'_{ijk} L_i Q_j D_k^c + \lambda''_{ijk} U_i^c D_j^c D_k^c \ , \qquad (20)
$$

where i, j, k are the generation indices and we assume that possible bilinear terms $\mu_i L_i H_2$ can be rotated away. L_i and Q_i are the $SU(2)$-doublets for lepton and quark superfields and E_i^c, U_i^c and D_i^c are the singlet superfields. λ_{ijk} and λ''_{ijk} are antisymmetric under the interchange of the first two and last two indices. The first two terms violate lepton numbers where as the last term violates baryon number. For our purpose we will consider only the lepton number violation contributions. As the λ type couplings do not contribute to the nonleptonic decays we obtain from eqn. (20) the following effective Hamiltonian due to the exchange of sleptons as

$$
\mathcal{H}_{\not{R}_p}^{eff} = \sum_{n,p,q=1}^{3} \frac{\lambda'_{npi} \lambda'^{*}_{nql}}{M_{\tilde{l}_n}^2} V_{kq} V_{jp}^* (\bar{d}_i P_L u_j)(\bar{u}_k P_R d_l) \qquad (21)
$$

with $P_{L,R} = (1 \mp \gamma_5)/2$. From the above effective Hamiltonian we calculate the amplitude $\mathcal{A}_{\not{R}_p}(\Lambda_b \to p\pi)$ using the factorization approximation. The matrix elements of the $(S-P)(S+P)$ operators are obtained using the Dirac equation of motion. Assuming V_{CKM} is given by only down-type quark sector we obtain the dominant transition amplitude to be

$$
\begin{aligned}
\mathcal{A}_{\not{R}_p}^{eff} = \sum_{n,=2,3} \frac{\lambda'_{npi} \lambda'^{*}_{nql}}{M_{\tilde{l}_n}^2} V_{11} V_{11}^* \ \times \ i f_\pi \bar{u}(p_f) \Big[& R_1 \Big(f_1(m_\pi^2)(m_i - m_f) + f_3(m_\pi^2) m_\pi^2 \Big) \\
& + R_2 \Big(g_1(m_\pi^2)(m_i + m_f) - g_3(m_\pi^2) m_\pi^2 \Big) \gamma_5 \Big] u_{\Lambda_b}(p_i) \ . \qquad (22)
\end{aligned}
$$

Now considering the slepton mass to be 100 GeV, the present bounds on λ'_{ijk} are [11]

$$\lambda'_{211} < 0.09 \qquad \lambda'_{213} < 0.09 \qquad \lambda'_{311} < 0.16 \qquad \lambda'_{313} < 0.16 \tag{23}$$

we obtain the S and P-wave $R_{\not{R}_p}$ amplitudes to be

$$S_{\not{R}_p} < 1.626 \times 10^{-9} \qquad P_{\not{R}_p} < 3.474 \times 10^{-9} \tag{24}$$

After obtaining the transition amplitude in SM and $R_{\not{R}_p}$ model we now proceed to estimate the CP asymmetries. The parity violating (S wave) and parity conserving (P wave) amplitudes can be explicitly written as

$$\begin{aligned} S &= \lambda_u S_u + \lambda_c S_c + S_{\not{R}_p} \\ P &= \lambda_u P_u + \lambda_c P_c + P_{\not{R}_p} \end{aligned} \tag{25}$$

where $\lambda_i = V_{ib}V_{id}$, are the product of CKM matrix elements which contain the weak phases. The strong phases which arise from the perturbative penguin diagrams at one loop level, are contained in $S_{u/c}$ and $P_{u/c}$ i.e., $S_u = |S_u|e^{i\delta_u}$ etc. The corresponding quantities for the antihyperon decays are given as

$$\begin{aligned} \bar{S} &= -\left(\lambda_u^* S_u + \lambda_c^* S_c + S_{\not{R}_p}\right) \\ \bar{P} &= \lambda_u^* P_u + \lambda_c^* P_c + P_{\not{R}_p} \end{aligned} \tag{26}$$

Thus the CP violating rate asymmetry is given as,

$$a_{cp} = \frac{2\Big[Im(\lambda_u\lambda_c^*)\left(Im(S_uS_c^*) + Im(P_uP_c^*)\right) + Im(\lambda_u)[S_{\not{R}_p}Im(S_u) + P_{\not{R}_p}Im(P_u)]\Big]}{A} \tag{27}$$

where

$$\begin{aligned} A = \Big[&|\lambda_u|^2(|S_u|^2 + |P_u|^2) + |\lambda_c|^2(|S_c|^2 + |P_c|^2) + (|S_{\not{R}_p}|^2 + |P_{\not{R}_p}|^2) \\ &+ 2Re(\lambda_u\lambda_c^*)\left(Re(S_uS_c^*) + Re(P_uP_c^*)\right) + 2\sum_{i=u,c} Re(\lambda_i)(S_{\not{R}_p}Re(S_i) + P_{\not{R}_p}Re(P_i))\Big] \end{aligned} \tag{28}$$

Using the Wolfenstein parametrization for CKM matrix elements with values $A = 0.815$, $\lambda = 0.2205$, $\rho = 0.175$ and $\eta = 0.37$, we obtain the branching ratio and CP violating observables in RPV model using eqns. (5), (9) and (27) as

$$\begin{aligned} &Br(\Lambda_b \to p\pi) < 1.6 \times 10^{-4} \\ &a_{cp} \simeq 0.3\% \\ &A(\alpha) \simeq 8.8 \times 10^{-3} \end{aligned} \tag{29}$$

The corresponding quantities in the SM ($S_{\not{R}_p} = 0$ and $P_{\not{R}_p} = 0$) are given as

$$\begin{aligned} &Br(\Lambda_b \to p\pi) = 0.9 \times 10^{-6} \\ &a_{cp} = 8.3\% \\ &A(\alpha) = 2.3 \times 10^{-5} \end{aligned} \tag{30}$$

It can be seen from eqns. (29) and (30) that the effects of R-parity and lepton number violating couplings significantly modify the SM results of the branching ratio and CP asymmetry parameters for the decay mode $\Lambda_b \to p\pi$. The branching ratio and the asymmetry parameter ($A(\alpha)$) in RPV model are approximately $\mathcal{O}(10^2)$ times larger than the SM contributions whereas the rate asymmetry a_{cp} is nearly 10 times smaller than the SM result.

To summarize, in this work we have studied the effects of R-parity violating couplings on the direct CP asymmetry parameters in $\Lambda_b \to p\pi$ decay mode. Assuming factorization, we have used the nonrelativistic quark model to evaluate the form factors at maximum momentum transfer (q_m^2) and the extrapolation of the form factors from q_m^2 to the required q^2 value is done by using the pole dominance. Although there are significant uncertainties in our estimates as we have used the factorization approximation to evaluate the matrix elements of the four-quark current operators and taken all the R-parity violating couplings to be real, it is probably safe to say that the asymmetry parameter $A(\alpha)$ in $\Lambda_b \to p\pi$ decay is significantly larger than the corresponding asymmetry in the Standard Model.

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REFERENCES

[1] For a recent review, see for example, *The BaBar Physics Book*, ed. P. Harrison and H. Quinn, SLAC-R-504, (1998); Y. Nir, hep-ph/9911321.

[2] OPAL Collaboration, R. Akers et al., Z. Phys. **C 69**, 195 (1996); Phys. Lett. **B 353**, 402 (1995); OPAL Collaboration, K. Ackerstaff et al, Phys. Lett. **B 426**, 161 (1998).

[3] CDF Collaboration, F. Abe et al, Phys. Rev. **D 55**, 1142 (1997): UA1 Collaboration, C. Albarjar et al., Phys. Lett. **B 273**, 540 (1991): CDF Collaboration, F. Abe et al., Phys. Rev. **D 47**, 2639 (1993); P. Abreu et al., Phys. Lett. **B 374**, 351 (1996).

[4] C. S. Aulakh and R. N. Mohapatra, Phys. Lett. **B 119**, 136 (1982); F. Zwirner, Phys. Lett. **132**, 103 (1983); I.-H. Lee, Nucl. Phys. **B 246**, 120 (1984); J. Ellis et al, Phys. Lett. **B 150**, 142 (1985); G. G. Ross and J. W. F. Valle, Phys. Lett. **151**, 375 (1985); S. Dawson, Nucl. Phys. **B 261**, 295 (1985); R. Barbieri, A. Masiero, Nucl. Phys. **B 267**, 679 (1986): S. Dimopoulos and L. Hall, Phys. Lett. **B 207**, 210 (1987).

[5] J. F. Donoghue and S. Pakvasa, Phys. Rev. Lett **55**, 162 (1985); J. F. Donoghue, X-G. He and S. Pakvasa, Phys. Rev. **D 34**, 833 (1986); D. Chang, X-G. He and S. Pakvasa, Phys. Rev. Lett. **74**, 3927 (1995); X-G. He, H. Steger and G. Valencia, Phys. Lett. **B 272**, 411 (1991); X-G. He and G. Valencia, Phys. Rev. **D 52**, 5257 (1995); J. Tandean and G. Valencia, Phys. Lett. **451**, 382 (1999).

[6] M. Bander, D. Silverman and A. Soni, Phys. Rev. Lett. **43**, 242 (1979); J. M. Gérard and W. S. Hou, Phys. Rev. **D 43**, 2909 (1991).

[7] J. F. Donoghue, E. Golowich, A. A. Petrov and J. M. Soares, Phys. Rev. Lett. **77**, 2178 (1996).

[8] Y. H. Chen, H. Y. Cheng, B. Tseng and K. C. Yang, Phys. Rev. **D 60**, 094014 (1999).

[9] H. Y. Cheng and B. Tseng, Phys. Rev. **D 53**, 1457 (1996).

[10] C. Caso et al, Euro. Phys. J. **C 1**, 1 (1998).

[11] H. Dreiner, hep-ph/9707435.